



Evaluation of hydraulic excavator Human–Machine Interface concepts using NASA TLX



Joseph Akyeampong^{a,*}, Silvanus Udoka^b, Giandomenico Caruso^c, Monica Bordegoni^c

^a Department of Industrial and Systems Engineering, North Carolina A&T State University, 1601 East Market Street, Greensboro, NC 27411, USA

^b Department of Management, North Carolina A&T State University, Greensboro, NC, USA

^c Dipartimento di Meccanica, Politecnico di Milano, Milan, Italy

ARTICLE INFO

Article history:

Received 20 February 2013

Received in revised form

28 June 2013

Accepted 11 December 2013

Available online 13 March 2014

Keywords:

Hydraulic excavator

Human–Machine Interface

Heads-up display

Coordinated control

Ergonomics

NASA TLX

ABSTRACT

This study evaluated newly proposed Human–Machine Interface (HMI) design concepts for improving the ergonomics of hydraulic excavators. The design concepts were based on an augmented interaction technique which involved the use of heads-up display (HUD) and coordinated control as HMI elements. Two alternative HMI designs were elaborated in order to separately evaluate the ergonomic impacts of the head-up display and the coordinated control by comparing them to the standard HMI design. The effectiveness of these three HMI designs in terms of the reduction of the operators' mental and physical workload were assessed by conducting experiments utilizing human subjects, ages 23–35 years. The *National Aeronautics and Space Administration's Task Load Index (NASA TLX)* method was used for collecting subjective workload scores based on a weighted average of ratings of six factors: Mental Demand, Physical Demand, Temporal Demand, Own Performance, Effort, and Frustration Level. The results showed that the type of HMI design affects different aspects of the operator's workload. Indeed, it showed how the proposed augmented interaction is an effective solution for reducing the ergonomic gaps in terms of mental workload, and to a lesser extent the physical workload, subjected by the standard HMI design. *Relevance to industry:* This study proposes innovative HMI solutions featuring heads-up display and coordinated control to improve the ergonomics of the hydraulic excavator HMI, particularly in reducing the operators' mental and physical workload. The results of this study promises to be an innovative approach for developing new HMI designs by hydraulic excavator manufacturers.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

1.1. Background

Hydraulic excavators (Fig. 1) have become a powerful earth-moving vehicle due to continual development and associated interminable need for more buildings, roads, bridges, mines, and dams etc., which require earth removal, heavy lifting and material transport, among other things, to construct them. Hydraulic excavators have a unique look with a front manipulator that mimics the human arm, a cab mounted on a pivot point, with an undercarriage that has wheels, or more commonly, tracks. The front manipulator comprises of the boom, dipper and bucket.

1.2. Problem

Despite its usefulness, operating a hydraulic excavator can be a cumbersome undertaking for many operators (novice or expert) because its Human–Machine Interface (HMI) is not easy to use. The typical excavator HMI combines a 2D monitor for displaying status information, and controls including a pair of joysticks for controlling the manipulator, and levers and pedals for motion control (Fig. 2). As shown in Fig. 3, there are two popular control standards (or patterns) used by manufacturers in designing the specific arrangement and direction of motion for the primary controls used for operating the hydraulic excavator – the ISO and SAE standards (Heavy Equipment Forums, 2006). The major difference in the two standards is the position of the boom and dipper control functions. In the SAE standard, the left joystick operates the dipper and swing; and the right joystick operates the boom and bucket. In the ISO standard, the boom and swing are controlled by the left joystick; and the right joystick controls the dipper and bucket. Some manufacturers offer designs in which operators can switch between the

* Corresponding author. Tel.: +1 336 450 8153.

E-mail addresses: joakyeam@gmail.com (J. Akyeampong), udoka@ncat.edu (S. Udoka), giandomenico.caruso@polimi.it (G. Caruso), monica.bordegoni@polimi.it (M. Bordegoni).



Fig. 1. Modern hydraulic excavator (Hitachi Construction Machinery America, 2004).

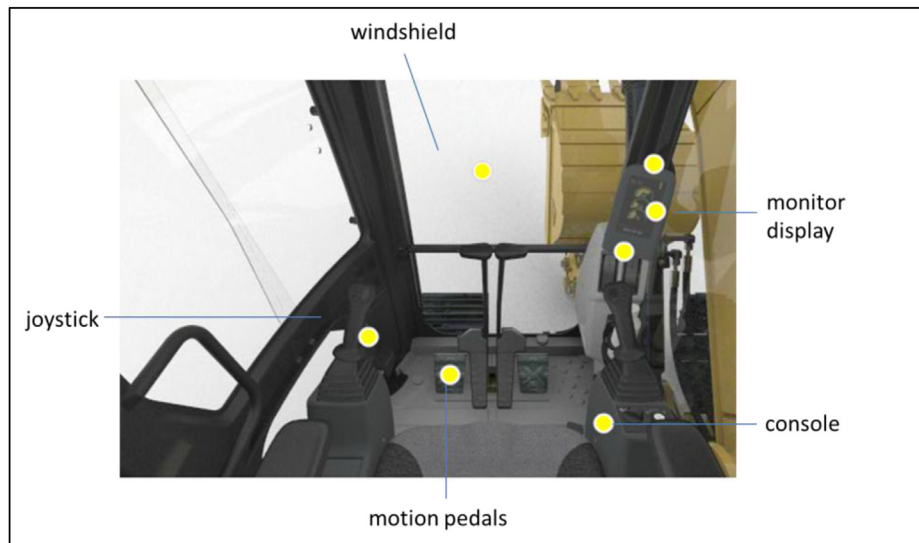


Fig. 2. The typical HMI design of hydraulic excavators (Caterpillar, 2009).

two patterns based on which one is most familiar to them (Aubrey, 2008).

Although the HMI of an excavator appears simple in design, as seen from the few elements that it comprises of, developing the

needed skills to effectively operate the hydraulic excavator requires years of on-the-job training and education (Wang and Dunston, 2007; Langer et al., 2012). Additionally, existing HMI designs present a number of ergonomic design gaps such as inadequate

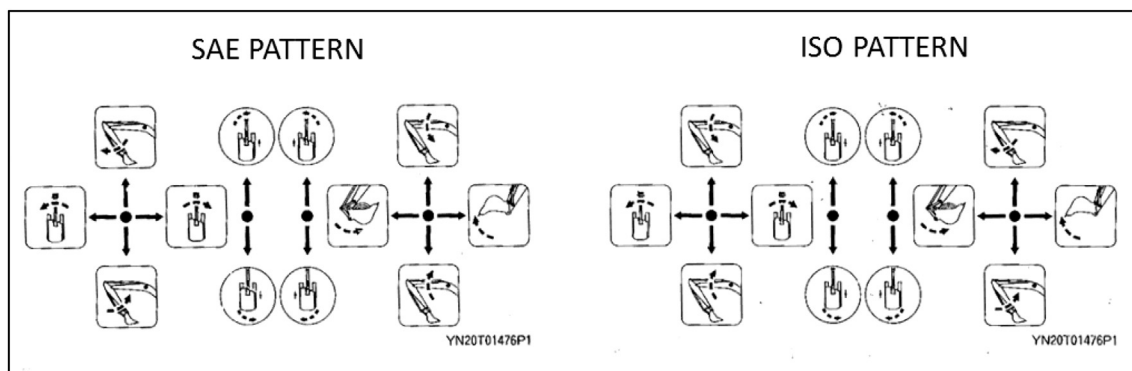


Fig. 3. Excavator control standards (Heavy Equipment Forums, 2006).

information feedback, poor work visibility, and repetition with control usage. These gaps negatively impact operator performance by subjecting them to undue mental and physical workload, causing a reduction in productivity through impaired concentration and fatigue. They also result in longer motion trajectories, decreasing efficiency and increasing energy costs.

1.3. Research gap

Considerable amounts of research have been published on improving the operational and technical performance of hydraulic excavators. Many of these researches have been focused on modelling of technical aspects of the system; there is little documented research where the human operator is considered as an essential part of the total system. Developing innovative HMI solutions is therefore needed in order to overcome the aforementioned HMI design gaps, and enhance overall system performance – both human and technical. Such a need has been underscored by some researchers in the field (Filla, 2005; Hughes and Jiang, 2010). Yet little research work has addressed this need, and more research is still needed to improve the design of the HMI of hydraulic excavators. Some documented research on HMI design improvements are presented below.

Kittusamy (2003) developed a checklist for evaluating cab design of construction equipment including hydraulic excavators. The checklist helped in identifying characteristics of the cab design that needed improvement (including control and seat design improvement), providing the critical point of departure in initiating future ergonomic analysis. Hughes and Jiang (2010) developed human performance and task simulation models to characterize the impact of different joystick control types (hydraulic vs. electronic joysticks) and expertise on operator workload and performance. They found that both control type and expertise had a significant impact on workload and operator performance and recommended that designers consider the placement of controls and measures to reduce operator workload for better performance in future systems. In a quest to improve the effectiveness of the HMI in future designs, Elton (2009), and Hayn and Schwarzmann (2010), proposed a multimodal operational concept which employs a haptically-enabled coordinated control scheme. This new operational concept uses a type of control equipped with tactile feedback, whose segments resemble the parts of the excavator's front manipulator. Pilot tests conducted on this operational concept indicated that it was a viable solution for improving the ergonomics of the HMI. In a recent study, Akyeampong et al. (2013) sought to improve the design of the display by exploring a heads-up display concept for the HMI. They used digital human-modelling to investigate the ergonomic impact of the heads-up display against the standard monitor display in terms of postural requirements and stresses imposed, and found the heads-up display concept to reduce awkward postures and stresses.

One investigation that is important but has not been conducted relates to how the different sources of workload which operators are likely to be subjected to can be characterized for existing and new HMI design concepts. To this end, this work presents a study involving the use of a subjective workload estimation methods to characterize the subjective workload demands of new hydraulic excavator HMI design concepts against the existing standard HMI. Although quantitative physiological measures such as electroencephalograph (EEG) and electromyography (EMG) provide more objective ways of assessing the relationship between operational skills and physical workload, these analyses are more obtrusive and can negatively influence the execution of the task since the sensors must be tethered to the subject. Consequently, the NASA TLX was chosen among the subjective workload estimation methods

(including SWAT, NASA-TLX, and Workload Profile Methods) because it is one of the most widely used and has achieved some solid goals in human factors research (Miller, 2001; Rubio et al., 2004). The NASA TLX has been successfully applied to measure and characterize subjective workload of HMIs in domains including the automobile (Broström et al., 2011; Matthews et al., 2003; Newell and Mansfield, 2008; Sodnik et al., 2008), aerospace, (Collet et al., 2009; Lehrer et al., 2010; Lin et al., 2012; Yiyuan et al., 2011; Zhang et al., 2009), medical (Anders et al., 2012; Effken et al., 2008; Pennathur et al., 2011) and process control (Chi et al., 2012; Hwang et al., 2008; Yang et al., 2012).

1.4. Proposed solution

Unlike automobiles and aircraft, where HMI has evolved into more user-friendly interfaces that provide users with enriched interaction experiences, the hydraulic excavator HMI has maintained a basic design over many decades, with limited incremental technological changes; significant improvements have been realized mainly in advanced electronics for the monitor display and pilot proportional control for the joysticks. In this study, new HMI concepts were proposed for a hydraulic excavator. These solutions are based on an augmented interaction style that employs a heads-up display and a coordinated control (a six degree-of-freedom haptic device). Two HMI design concepts based on this interaction style were created. Design A utilized a heads-up display with coordinated control; and Design B utilized a heads-up display with joystick controls. Both of these design concepts were compared with the standard HMI (Design C: monitor display with joystick controls). Based on these design concepts, we hypothesized that: new interaction schemes in the form of augmented interaction for designing the HMI for hydraulic excavators (Designs A and B) would yield a lower subjective workload among operators compared to the current state-of-the-art HMI (Design C). A mixed reality simulator deploying a seating buck was developed to simulate, test and evaluate the ergonomics of the three HMI design concepts. Experiments were conducted using human participants to evaluate the workload demands of each of the three HMI design concepts using the NASA TLX after the participants have completed a simulated rock excavation task.

2. Apparatus: the mixed reality seating buck simulator

A mixed reality seating buck simulator (Fig. 4) was used to assess the three HMI designs. Its effectiveness, as a system for ergonomic evaluation, has been previously assessed in a study conducted in the automotive field (Bordegoni and Caruso, 2012). The seating buck is a reconfigurable system that consists of computer-generated graphics (virtual objects) and physical devices mixed together to mimic the interior of a vehicle. The initial seating buck was modified in this study to obtain the platform for prototyping, testing and evaluating the hydraulic excavator HMI designs. The modified seating buck was comprised of five modules: *main module*, *graphics and computing module*, *display module*, *tracking module*, and *interaction module*.

The main module served as the chassis or support structure for the seat and other hardware devices. The structure was made out of aluminium profiles and users were able to adjust the seat and supports for the controls so that they could orient these elements to a comfortable position. On it, the two different controls (joysticks and coordinated control) were changed for their respective HMI being tested. The graphics and computing module consisted of computers for generating the virtual environment/task scenario and display visualizations, establishing the necessary communication protocols, and obtaining simulation output data. 3D models

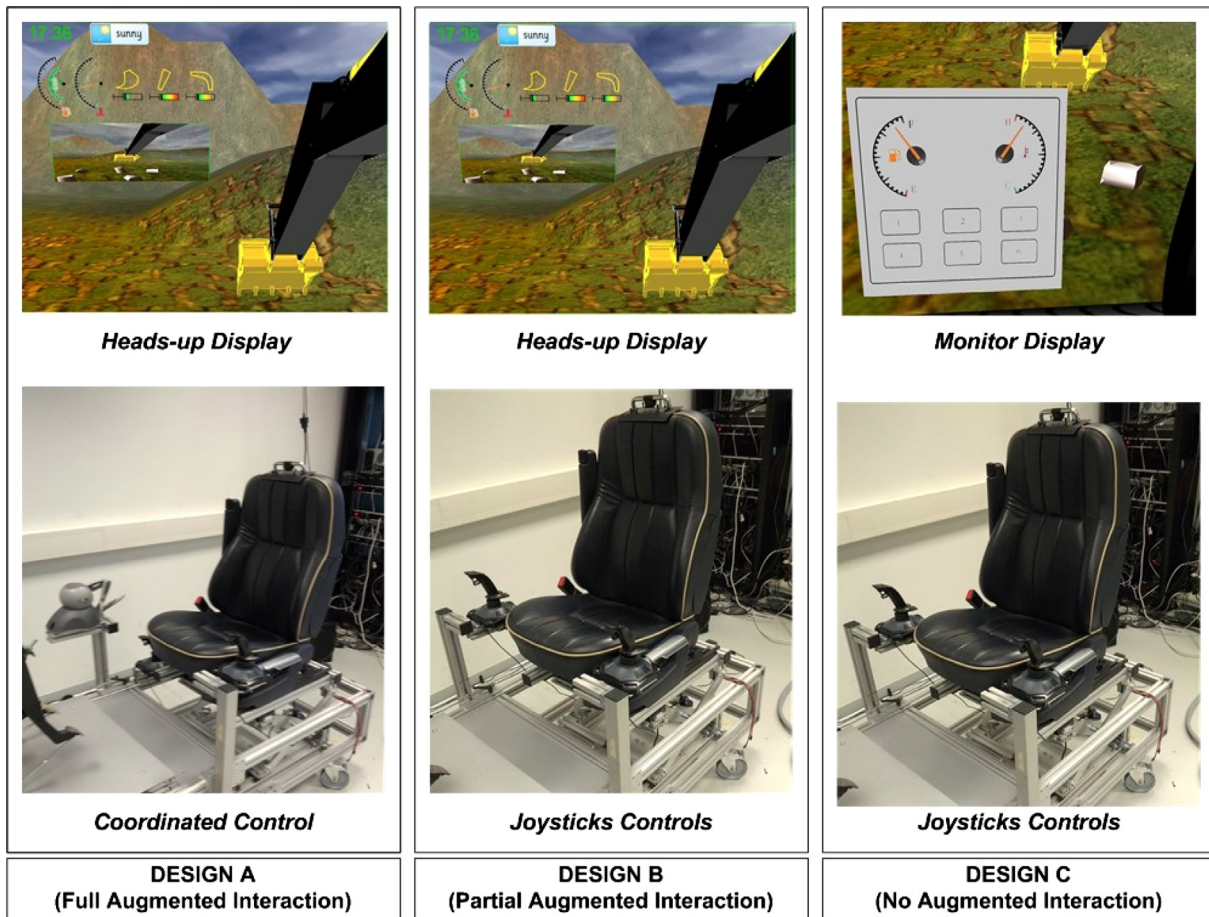


Fig. 4. The seating buck mixed reality showing the three HMI designs.

of an excavator and dumptruck were created with a CAD software and imported into Virtools 5.0, which was the software used for generating the virtual environment and rock excavation task scenario.

An immersive mixed reality environment was provided with the display module. This was an Optical See-Through Head-Mounted Display (OST-HMD) – the nVisor ST60 (NVIS Technology, 2012). With this display, users were shown a forward view point of the windshield as would be experienced in a real excavator cab. It was also used to present the visualization of the heads-up and monitor displays. The heads-up display was overlaid on the visor in the field of view of the user, but toward the right side of the virtual windshield. The monitor display was modelled as a 3D monitor and positioned at the bottom right side of the cab as seen in real life. The main difference between these two displays was in the type of visualization that they provided. In addition to the traditional gauges that provided status information (i.e. oil and fuel level, engine temperature etc.), by including a bucket camera to provide a video feedback to enhance work visibility and information about environmental conditions (such as weather information), the heads-up display provided more enriched work zone information.

The tracking module used an Optitrak VR100:R2 optical motion capture system (OptiTrak™, 2012) equipped with 6 infrared cameras for accurately tracking and aligning user movements with updates in the virtual objects. The interaction module employed a Sensable Phantom Omni haptic device (Sensable™, 2011) for simulating the coordinated control and a pair of Logitech joysticks (Logitech™, 2012) for simulating the joystick controls.

The three HMI designs were, therefore, defined as shown in Fig. 4 follows: Design A (heads-up display with coordinated control; referred to as “full augmented interaction”); Design B (heads-up display with joystick controls; referred to as “partial augmented interaction”); and Design C (monitor display with joystick controls; referred to as “no augmented interaction”).

3. Methods

The NASA TLX was the tool used to characterize the workload that the operator was subjected to by each of the three HMI designs. The NASA TLX provides a multidimensional rating procedure that allows for collecting subjective workload scores based on a weighted average of ratings of six subscales (or factors). The six subscales include: Mental Demand (MD), Physical Demand (PD), Temporal Demand (TD), Own Performance (OP), Effort (EF), and Frustration Level (FL). The first three of the six subscales relates to the workload demands imposed on the subject; and the remaining three to the subject’s interaction with the task. Each subscale is described in the Appendix. A computerized version of the NASA TLX was used to obtain the subjective workload scores. Before scoring, each subject was trained on the connotation of the six sub-scales of the NASA TLX method, and also familiarized with how to use the computer version for scoring. The scoring with the NASA TLX involved a two-part evaluation procedure consisting of weights and ratings. To obtain the weight of each scale, subjects’ were asked to provide responses to 15 possible pair-wise comparisons among the six subscales, to collate the degree to which each of the six

subscales contributed to their workload. The weight was, therefore, determined by tallying the number of times that the subject circled a particular sub-scale on the pair-wise comparisons. In order to obtain the magnitude ratings, subjects responded by marking each subscale on a 12 cm line divided into 20 tick marks anchored by bipolar descriptors, High/Low. The 21 vertical tick marks on each scale divide the scale from 0 to 100 in increments of 5. Each subscale was rated by moving the needle on the line to a tick mark location, which was based on the subject's perception of the contribution of the given subscale to the workload of the task.

3.1. Participants

Twenty subjects were recruited for the experiment and were selected among a university community and a prerequisite for participation was that the subject has to be in good health without any history of visual and musculoskeletal health problems. Approval for conducting the experiment was obtained from the Institutional Review Board of the Office of Research Compliance at North Carolina A&T State University. Table 1 shows the characteristic of the involved subjects. Values are presented as the mean $\pm$ standard deviation with ranges in parentheses.

3.2. Task description

The task scenario that was simulated involved the excavation of rocks. The goal of this task was to dig up rocks placed at vantage locations on a worksite, and dump them into a dumptruck bed (Fig. 5).

To accomplish the task goal, the test subjects were required to perform a move-dig-move-dump work cycle. The subject must first move the excavator to the rock, dig up a load, and move the excavator with properly positioned bucket of the dug rock to dump into the dumptruck located at a fixed position on the worksite. Five rocks were randomly placed in the scene within an arbitrary work envelope, each representing a bucket-load of after a dig. Thus, subjects were required to perform five replications of the task (move-dig-move-dump work cycle). The location and distance of the rocks from the dumptruck were unknown to the subject. This was done to introduce some degree of difficulty and judgement, by requiring the subject to do several manipulations with the controls, combined with cognitive processing of displayed information in order to accomplish the task goal. To be able to locate the rock, the subject was required to use the drive control buttons on the joystick to drive towards the rock. To be able to dig and dump the rock, the subject was required to apply the necessary combinations of the joystick movements to control the boom, arm and bucket.

3.3. Experimental procedure

A completely randomized, within-subject experimental design was employed. With this type of design, each subject was made to test the three HMI designs in a randomized order. A counterbalancing randomization technique was used to vary the order of the test runs in order to reduce transfer of learning effects. The entire experiment, which was divided into four sessions, lasted a

Table 1

Subject characteristics for height, body mass and age.

	Height (cm)	Body mass (kg)	Age (years)
Males	176.1 $\pm$ 7.6 (164–190)	74.8 $\pm$ 14.1 (60–109)	27.4 $\pm$ 3.5 (23–35)
Females	160.0 $\pm$ 4.2 (154–163)	56.8 $\pm$ 5.0 (52–62)	28.5 $\pm$ 3.1 (25–32)
Total	172.9 $\pm$ 9.6 (154–190)	71.2 $\pm$ 14.7 (52–109)	27.6 $\pm$ 3.3 (23–35)

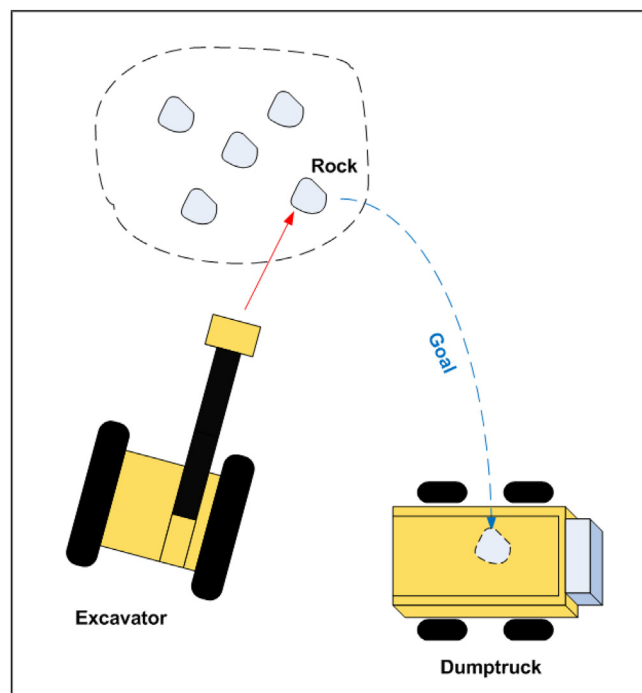


Fig. 5. Graphical representation of the task scenario: the user must approach the rock with the excavator, dig up the rock with the bucket and dump it into the dumptruck bed.

total of 90 min. In the first session, prior to inviting participants to conduct the testing, the seating buck was configured to fit the HMI design to be tested. The duration for this session was 5 min. In the second session, the participant was welcomed to the study and asked to provide their background information including: age, sex, height and weight. Next, a tutorial was given to familiarize the subject with the testing procedure, including how the display and controls of the HMI designs worked, after which the participant performed an initial test run. The duration for this session was 10 min. In the third session, after the seating buck had been setup and the participant had been familiarized with each HMI simulation, the actual test was conducted (Fig. 6). Each participant was presented with simulations of each HMI design in a random order, with which they were required to complete the rock excavation task. The five rocks to be excavated were presented in the scene during each HMI simulation run. A maximum allowable task completion time of 15 min was established as the benchmark time for completing the task. This time was obtained in a pilot test with three independent subjects who were not part of the twenty subjects who performed the evaluation. It was based on an average task completion time of 10 min plus an allowance time of 5 min. After one HMI simulation run had been completed, subjects were given 5 min to rest and to recover from any mental and physical workload before starting the next HMI simulation run. This time was also used to reconfigure the seating buck for the next HMI design to be tested. The total time allotted for this session was 60 min. In the fourth and final session, the NASA Task Load Index was used to obtain the subjective workload ratings for each of the three HMI designs. This lasted 15 min per participant. The ratings of all three HMIs were done after the subject had completed the experiment because an assessment of the reliability of the NASA TLX in terms of user ratings has been tested in a variety of user tasks including helicopter simulation and supervisory control. It was shown that, when ratings were done before each condition or after all conditions (retrospectively), little information was lost in the

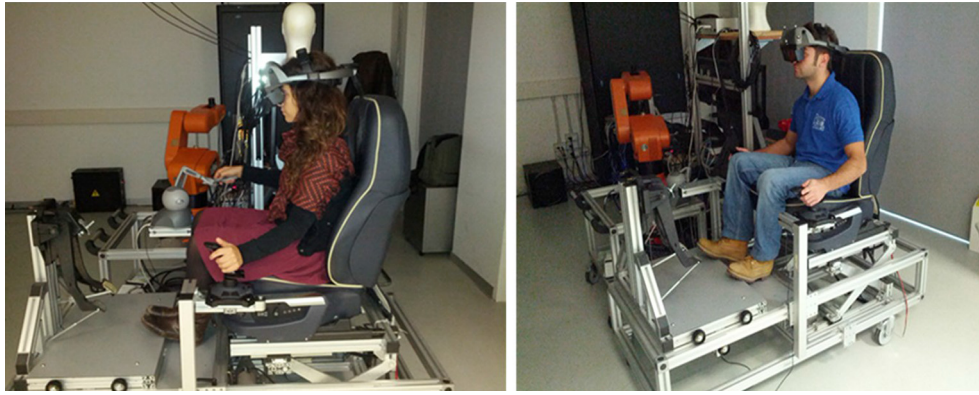


Fig. 6. Female and male test participants interacting with simulated HMI designs.

latter case; a high correlation existed between rating that were done before and after the simulations.

4. Results

The mean subjective workload ratings for each subscale for Designs A, B and C is summarized in Tables 2–4 respectively; and their graphical compositions are shown in Figs. 7–9 respectively. Overall, the Mental Demand (MD) recorded the highest mean workload score across all the three HMI Designs. This was followed by Own Performance (OP), Effort (EF), Frustration Level (FL), Temporal Demand (TD) and Physical Demand (PD) respectively. The weighted ratings are shown as the dependent measure on the y-axis and the six workload subscales are shown as the independent measures on the x-axis. The width of the subscale bar reflects the weight (or the relative importance) assigned to it, with the value of the weight on top of the bar; the height of the bar represents its rating. The adjusted workload rating is, therefore, the area of the subscale bar obtained as the product of the weight and the rating.

The overall weighted rating for each HMI design was obtained by dividing the sum of the adjusted workload score across the six subscales by 15. These are summarized shown graphically in Fig. 10. Design B had the least overall workload score, followed by Design A, and Design C respectively.

5. Discussion

The results of the subjective workload scores from the NASA TLX showed that Mental Demand (MD) induced the highest workload across all three HMIs. This partially confirms the research problem statement that the operation of the hydraulic excavator is a mentally demanding job. Within the scope of this research was to achieve a reduction in the operator's mental workload, afforded by an improved HMI design that enhances cognition through providing richer work-space information for accomplishing task goals. To this end, the heads-up display was proposed as a vital component for providing a potential solution to the mental workload problem. The results of a simulated concept of the heads-up display as reflected by Designs A and B showed that users experienced less mental workload with this type of display. Overall, there was an improvement in the mental workload with the new designs. When compared to Design C, the mental workload was reduced by 28.38% for Design A, and 35.39% for Design B.

In addition to MD, OP and EF also received high ratings in contributing to the workload of the operator across all three HMIs. The high scores translated to users feeling they performed poorly and had to exert a substantial amount of effort to accomplish the

goals of the task. The reason that can be attributed to this outcome is that all the users who tested the three HMI designs were novices and did not have relevant experience with operating a hydraulic excavator. Nevertheless, since they were all able to complete the task within the allowable time without prior knowledge or exposure implies that when given time to completely develop the skills needed to operate a hydraulic excavator (as in training), their performance can be significantly enhanced and the amount of effort required can also be significantly reduced. Only marginal differences were recorded in OP workload between the new HMI designs. When compared to Design C, the workload due to OP increased by 4.68% for Design A, and by 26.51% for Design B. The contribution of EF to workload increased by 4.05% with Design A

Table 2
NASA TLX data summary for Design A.

Subscale	Weight	Rating	Adjusted score
MD	3	57.20	171.6
TD	1	26.80	26.80
PD	2	35.95	71.9
OP	3	48.05	144.15
EF	3	47.50	142.5
FL	3	50.60	151.8
Weighted sum			708.75

Table 3
NASA TLX data summary for Design B.

Subscale	Weight	Rating	Adjusted score
MD	3	51.60	154.8
TD	1	26.45	26.45
PD	2	38.35	77.7
OP	4	43.55	174.2
EF	3	42.65	127.95
FL	2	39.70	79.4
Weighted sum			640.50

Table 4
NASA TLX data summary for Design C.

Subscale	Weight	Rating	Adjusted score
MD	4	59.90	239.6
TD	1	29.55	29.55
PD	2	43.50	87
OP	3	45.90	137.7
EF	3	45.65	136.95
FL	2	45.75	91.5
Weighted sum			722.30

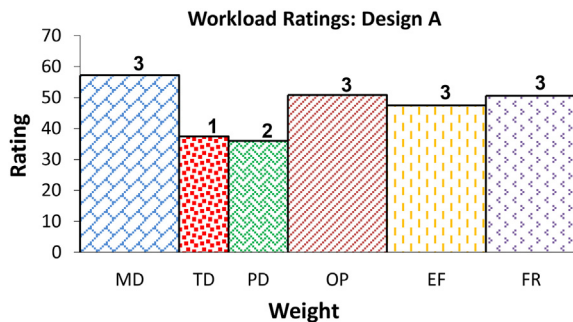


Fig. 7. Plot of NASA TLX workload ratings for Design A.

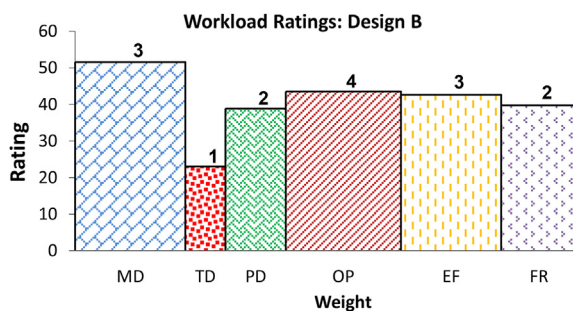


Fig. 8. Plot of NASA TLX workload ratings for Design B.

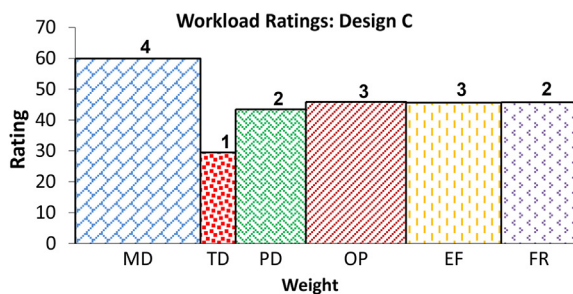


Fig. 9. Plot of NASA TLX workload ratings for Design C.

compared to Design C, and decreased by 6.57% with Design B compared to Design C.

Frustration Level FL was also an important dimension that contributed to operator workload. Workload due to FL was highest for Design A with a 65.9% increase over Design C, and lowest for Design B with a 13.22% decrease. The coordinated control

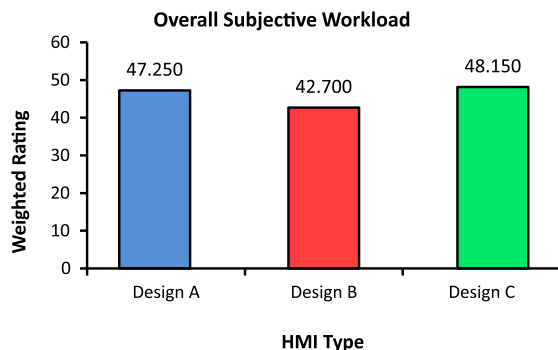


Fig. 10. Plot of overall workload ratings for Design A, B and C.

(phantom) was found to be the source of the higher FL workload rating associated with Design A. The frustration was seen to have originated from the coordinated control. This control type was too sensitive and lacked resistance in the links, thereby allowing free hand movements. Small amounts of these hand movements resulted in larger motions of the excavator, making it difficult to control. This was consistent with the observation made by Elton (2009). A solution to this would be to introduce some stiffness in the links.

The results also showed that PD had a remarkable impact on the operator's workload. This also serves to partially confirm the research problem that the standard HMI design subjects operators to some undue amount of physical workload. Much of the physical of workload comes from repetitive use of the joysticks and long operating hours, typically in the range of 6–8 h (Kuijt-Evers et al., 2003). However, because the simulation time was short in this study, the effect of long operating hours was not examined. In terms of the physical impacts of the controls, evidence is provided that the phantom, despite its sensitivity, was effective in reducing the PD. Compared to Design C, there was reduction in workload due to PD for both Design A (17.36%) and Design B (10.69%).

The Temporal Demand (TD) showed the least contribution to operator workload. TD is influenced by such things as time pressure and speed of the task. These variables did not affect participants, hence the result for the low ratings. The TD workload showed a decrease for Design A (9.31%) and Design B (10.49%).

Finally, in terms of the overall workload reduction from Design C, Design B resulted in an 11.32% change, whereas Design A exhibited a 1.87% change. The results of the NASA TLX thus provide support for the proposed HMI designs as being effective solutions for reducing the ergonomics gaps in terms of mental workload, and to a lesser extent the physical workload, subjected by the standard HMI.

All the above conclusions are derived from descriptively comparing the overall subjective workload ratings as well as the sub-scale ratings with each other. This is because a test of significance using ANOVA showed no significant differences of HMI type with the subjective workload scales. The non-parametric Mann–Whitney *U* Test was also used yet no significant differences were shown. Thus our hypothesis was only supported by descriptive statistics. Nevertheless, we present the results to demonstrate the viability of the proposed augmented interaction technique for hydraulic excavators – hence, that is how the results must be taken and interpreted in the present paper. We attribute the lack of a significant difference to the number of participants used in the study and their skills level. We assert that when the sample size is increased, and expert operators are used to evaluate the designs, significant effects could be noticeable. This has been stated in the paper as future work that is requisite to enhance the reliability and scientific value of this study.

5.1. Implications for design

The above analysis indicated that the proposed HMI designs show promise as viable solutions to addressing the ergonomic gaps in the standard HMI. Nevertheless, both designs also had their pros and cons. The major strength in both HMIs designs was the heads-up display concept, which showed a reduction in the mental workload and to a lesser extent the physical workload of the participants. The con was the control type. The coordinated control did not show much promise. Based on this, we cannot conclude that either design is the ultimate design. Rather, both HMIs offer two design options for designers to consider. However, since this work only sought to demonstrate the viability of the new HMI solutions, the results obtained in this work cannot be taken to be conclusive;

and further work in advancing the designs proposed herein, including thorough ergonomic testing, are necessary to provide more robust results for recommending an improved HMI design for the hydraulic excavator.

6. Conclusion and future work

This study characterized the effect of hydraulic excavator HMI design concepts on subjective workload demands. The goal of the research was to obtain a more usable and ergonomic HMI concepts for the hydraulic excavator. To this end, two alternative HMI design concepts based on an augmented interaction style, which involved the use of a heads-up display with coordinated control, and heads-up display with joystick controls respectively, were created and compared to the standard HMI design. The six subscales of the NASA TLX subjective workload assessment tool were used to obtain the workload ratings for characterizing each HMI design. The results showed a reduction in the MD and PD with the new HMI design concepts. Based on the results of the study, we conclude that the new HMI designs can be an effective solution for addressing the ergonomics gaps in the standard HMI design.

It must pointed out, however, that for the heavy mobile equipment industry to try out the solutions proposed by this work, future studies are needed before generalizations can be made about the effectiveness of the proposed solution, as well as provide substantial evidence for their technical implementation. First, the proposed concepts, i.e. the HUD and coordinated control scheme, need to be refined and properly simulated in order to allow for a more rigorous ergonomics evaluation. For example, the elements of the display must be evaluated to identify those elements that enhance the operator's situational awareness – for example, by using eye tracking. Also, since the results showed that the mental workload appeared, in subjective terms, to have been solved as reflected in the reduction in MD of the proposed HMI concepts, the problem of physical workload was not adequately addressed as revealed by the level of frustration yielded by the proposed coordinated control scheme. Thus, future simulations will have to consider the sensitivity in the links of the coordinated control and its positioning of the on the seating buck. Second, expert operators must be used in evaluating the concepts in order to provide results that can be used to draw more realistic conclusions.

Acknowledgement

This work was supported by the Virtual Prototyping Lab of the Department of Mechanical Engineering at Politecnico di Milano, Milan, Italy.

Appendix A

Title	End points	Description
Mental demand	Low/high	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical demand	Low/high	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal demand	Low/high	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was

(continued)

Title	End points	Description
Own performance	Good/poor	the pace slow and leisurely or rapid and frantic? How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Effort	Low/high	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration level	Low/high	How insecure, discouraged, irritated, stressed, and annoyed or secure, gratified, content, relaxed, and complacent did you feel during the task?

References

- Akyeampong, J., Nevins, L., Udoka, S.J., 2013. Using digital human modeling to enhance work visibility for excavator. In: Paper Presented at the 2013 Industrial and Systems Engineering Research Conference.
- Anders, S., Alberth, R., Millera, A., Weinger, M.B., Doig, A.K., Behrense, M., Aguttere, J., 2012. Evaluation of an integrated graphical display to promote acute change detection in ICU patients. *Int. J. Med. Inf.* 81 (12), 842–851.
- Aubrey, J., 2008. Breaking Down Backhoe Loaders. Utility Contractor: September 2008 Feature Story. <http://www.utilitycontractoronline.com/archives/featurestory/2008/09-08-featurestory1.html>.
- Bordegoni, M., Caruso, G., 2012. Mixed reality distributed platform for collaborative design review of automotive interiors. *Virtual Phys. Prototyp.* 7 (4), 243–259.
- Broström, R., Bengtsson, P., Axelsson, J., 2011. Correlation between safety assessments in the driver-car interaction design process. *Appl. Ergon.* 42 (4), 575–582.
- Caterpillar, 2009. Hydraulic Excavators Vol. 2011 [Online] Available. <http://xml.catmms.com/servlet/ImageServlet?imageId=C480966>.
- Chi, H.-L., Chen, Y.-C., Kang, S.-C., Hsieh, S.-H., 2012. Evaluation of operators' mental workload of human–system interface automation in the advanced nuclear power plants. *Nucl. Eng. Des.* 239 (11), 2537.
- Collet, C., Averty, P., Dittmar, A., 2009. Autonomic nervous system and subjective ratings of strain in air-traffic control. *Appl. Ergon.* 40 (1), 22–32.
- Effken, J.A., Loeb, R.G., Kang, Y., Lin, Z.-C., 2008. Clinical information displays to improve ICU outcomes. *Int. J. Med. Inf.* 77 (11), 765–777.
- Elton, M., 2009. An Efficient Haptic Interface for a Variable Displacement Pump Controlled Excavator. Master's thesis. Mechanical Engineering, Georgia Institute of Technology.
- Filla, R., 2005. Operator and Machine Models for Dynamic Simulation of Construction Machinery. PhD thesis. Linköping University, Institute of Technology.
- Hayn, H., Schwarzmann, D., 2010. A haptically enhanced operational concept for a hydraulic excavator. In: Zadeh, M.H. (Ed.), *Advances in Haptics*, pp. 199–220. Vukovar, Croatia.
- Heavy Equipment Forums, 2006. How Many Patterns Are You Competent on?. <http://www.heavyequipmentforums.com/showthread.php?9-How-many-patterns-are-you-competent-on/page4>.
- Hitachi Construction Machinery America, 2004. Excavators [Online] Available: http://www.hitachiconstruction.com/en_US/cfd/construction/hitachi_const/pdf/brochures/excavator/d_series_construction_class.pdf.
- Hughes, K., Jiang, X., 2010. Using discrete event simulation to model excavator operator performance. *Hum. Fact. Ergon. Manuf. Serv. Ind.* 20 (5), 408–423.
- Hwang, S.-L., Yau, Y.-J., Lin, Y.-T., Chen, J.-H., Huang, T.-H., Yenn, T.-C., Hsu, C.-C., 2008. Predicting work performance in nuclear power plants. *Saf. Sci.* 46 (7), 1115–1124.
- Kittusamy, N.K., 2003. A checklist for evaluating cab design of construction equipment. *Appl. Occup. Environ. Hyg.* 18 (10), 721–730.
- Kuijt-Evers, L.F.M., Krausea, F., Vinka, P., 2003. Aspects to improve cabin comfort of wheel loaders and excavators according to operators. *Appl. Ergon.* 34 (3), 265–271.
- Langer, T.H., Iversen, T.K., Andersen, N.K., Mouritsen, O.O., Hansen, M.R., 2012. Reducing whole-body vibration exposure in backhoe loaders by education of operators. *Int. J. Ind. Ergon.* 42 (3), 304–311.
- Lehrer, P., Karavidas, M., Lu, S., Vaschillo, E., Vaschillo, B., Cheng, A., 2010. Cardiac data increase association between self-report and both expert ratings of task load and task performance in flight simulator tasks: an exploratory study. *Int. J. Psychophysiol.* 76 (2), 80–87.
- Lin, C.J., Lin, P.-H., Chen, H.-J., Hsieh, M.-C., Yu, H.-C., Wang, E.M.-Y., Ho, H.L.C., 2012. Effects of controller-pilot communication medium, flight phase and the role in the cockpit on pilots' workload and situation awareness. *Saf. Sci.* 50 (9), 1722–1731.

- Logitech, 2012. Logitech™ Attack 3 Joystick [Online] Available: <http://www.logitech.com/en-us/gaming/joysticks/attack-3-joystick>.
- Matthews, R., Legg, S., Charlton, S., 2003. The effect of cell phone type on drivers subjective workload during concurrent driving and conversing. *Accid. Anal. Prev.* 35 (4), 451–457.
- Miller, S., 2001. Literature Review: Workload Measures. University of Iowa Document (ID: N01-006).
- Newell, G.S., Mansfield, N.J., 2008. Evaluation of reaction time performance and subjective workload during whole-body vibration exposure while seated in upright and twisted postures with and without armrests. *Int. J. Ind. Ergon.* 38 (5–6), 499–508.
- NVIS Technology, 2012. nVisor ST60 [Online] Available: <http://nvisinc.com/technology.php?prod=nVisorSX>.
- OptiTrak, 2012. V100:R2 Optical Motion Capture System [Online] Available: <http://www.naturalpoint.com/optitrack/products/v100-r2/>.
- Pennathur, P.R., Cao, D., Bisantz, A.M., Lin, L., Fairbanks, R.J., Wears, R.L., Perry, S.J., Guarrera, T.K., Brown, J.L., Sui, Z., 2011. Emergency department patient-tracking system evaluation. *Int. J. Ind. Ergon.* 41 (4), 360–369.
- Rubio, S., Díaz, E., Martín, J., 2004. Evaluation of subjective mental workload: a comparison of SWAT, NASA-TLX, and workload profile methods. *Appl. Psychol. Int. Rev.* 53 (1), 61–86.
- Sensable, 2011. Haptic Devices [Online] Available: <http://sensable.com/products-haptic-devices.htm>.
- Sodnik, J., Dicke, C., Tomazic, S., Billingham, M., 2008. A user study of auditory versus visual interfaces for use while driving. *Int. J. Hum. Comput. Stud.* 66 (5), 318–332.
- Wang, X., Dunston, P.S., 2007. Design, strategies, and issues towards an augmented reality-based construction training platform. *Inf. Technol. Construct.* 12, 363–380.
- Yang, C.-W., Yang, L.-C., Cheng, T.-C., Jou, Y.-T., Chiou, S.-W., 2012. Assessing mental workload and situation awareness in the evaluation of computerized procedures in the main control room. *Nucl. Eng. Des.* 250, 713–719.
- Yiyuan, Z., Tangwen, Y., Dayong, D., Shan, F., 2011. Using NASA-TLX to evaluate the flight deck design in design phase of aircraft. *Proc. Eng.* 17, 77–83.
- Zhang, Y., Li, Z., Wu, B., Wu, S., 2009. A spaceflight operation complexity measure and its experimental validation. *Int. J. Ind. Ergon.* 39 (5), 756–765.